Clinical trials with neuroprotective drugs in acute ischaemic stroke

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Clinical trials with neuroprotective drugs in acute ischaemic stroke: are we doing the right thing?

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Ischaemic stroke is a leading cause of death and long-lasting disability. Several neuroprotective drugs have been developed that have the potential to limit ischaemic brain damage and improve outcome for patients. While promising results with these drugs have been achieved in animal stroke models, all Phase III trials conducted so far indicate that these drugs have failed to live up to their promise. Despite the limits of animal models, which cannot mimic the clinical situation, the disappointing results of neuroprotective trials might largely be due to methodological problems. Future trials with neuroprotective drugs should be performed in stroke (care) units, after sufficient information regarding therapeutic time window, dosage, duration of therapy and safety has been gathered from pilot studies, and a better selection of target patients has been made. Much of this information can now be obtained by techniques that visualize the penumbra, such as combined diffusion-weighted and perfusion MRI. Consideration should also be given to clinical trials with well-designed combinations of treatments.

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A TARGET for acute intervention in ischaemic stroke is the penumbra, a zone of incomplete cerebral ischaemia, where neurones are functionally inactive but still viable. The development of the penumbra is a time-limited condition where cells will die in the ensuing hours to days, owing to a cascade of biochemical events, the so-called 'ischaemic cascade' (see Box 1).

Compounds that interfere with these biochemical steps have been demonstrated to be neuroprotective in preclinical models of stroke. A fraction of these have entered clinical development and some of those that survived early safety trials have been studied in randomized double-blind placebo-controlled efficacy trials (Phase III trials). Such trials require the courageous participation of many stroke patients, a 24-hours-a-day commitment of physicians from many centres and usually significant financial investment from a pharmaceutical company. The resources required to complete such a trial are estimated to be about 30–40 million US dollars[1]. Despite these efforts, all Phase III trials have so far failed to demonstrate efficacy of neuroprotective agents (Table 1).

Na^+-channel blockers

The anticonvulsant phenytoin blocks voltage-dependent Na^+ channels and reduces infarct size in both permanent and reperfusion models of focal brain ischaemia in rodents[24,25]. Fosphenytoin is a prodrug of phenytoin that has been evaluated in a Phase III trial. Enrolment was halted after 462 patients had been included because no differences in primary or secondary endpoints were found in an interim analysis[2].

Ca^{2+}-channel blockers

One obvious treatment strategy for stroke involves the regulation of Ca^{2+} entry into the cell using inhibitors of voltage-sensitive Ca^{2+} channels. Nimodipine is an inhibitor of L-type Ca^{2+} channels, whereas flunarizine mainly acts as a T-type Ca^{2+}-channel blocker[26]. Both these compounds can reduce infarct size when administered shortly after permanent and transient focal cerebral ischaemia[26]. However, their potency is less than that of glutamate-receptor antagonists. Nimodipine has been studied most extensively and, in contrast to its beneficial effects in subarachnoid haemorrhage, it has produced unimpressive results in acute cerebral ischaemia. The intravenous administration even worsened outcome because of detrimental haemodynamic effects[8]. A meta-analysis covering nine studies with oral nimodipine (120 mg/day) suggested a possible benefit when the drug was given within the first 12 h after onset of symptoms[27]. The VENUS (very early nimodipine use in stroke) trial, which was conducted to confirm this hypothesis in a prospective manner, has been stopped because, in an interim analysis, no benefit of nimodipine became evident[9]. Clinical development of flunarizine in stroke has been suspended after negative results of the FIST (flunarizine in stroke trial)[10].

Glutamate inhibition or GABA stimulation

Inhibitors of glutamate receptors, particularly those that block NMDA receptors, can reduce infarction volume and neurological deficits in permanent and reperfusion models of focal cerebral ischaemia[28]. The use of several NMDA-receptor antagonists was discontinued in Phase I and Phase II studies because of unacceptable adverse effects. The major problems with these compounds are psychomimetic effects (agitation, hallucinations, paranoia and delirium), sedation, catatonia and concerns about potential neurotoxicity[29]. Only selfotel, a competitive antagonist at the NMDA binding site of the NMDA receptor, and aptiganel, a non-competitive

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Box 1. Neurotoxic cascade in ischaemic brain injury

Focal decrease of cerebral blood flow (CBF) to below 8–10 ml/100 mg/min produces rapid neuronal cell death. However, between this densely ischaemic core and the normally perfused brain (CBF of 50–55 ml/100 mg/min), there exists a zone of moderately reduced blood flow, the extent of which depends on the collateral supply from surrounding arteries. In this zone, called the penumbra, O_2 delivery becomes insufficient to allow normal levels of oxidative metabolism[a,b]. This produces lactic acidosis and curtails the production of ATP, the energy source of cellular ionic pumps. Failure of the Na^+–K^+ pump results in a rapid loss of K^+ from the neurones and massive neuronal depolarization occurs. This opens voltage-sensitive Ca^{2+} channels and leads to an extracellular build up of excitatory amino acids, which overstimulate excitatory-amino-acid receptors[a–c]. Acute elevation of glutamate activates the abundant number of glutamate receptors of which, notably, the NMDA and AMPA receptors are clearly implicated in the neurotoxic process. AMPA-receptor activation contributes to the depolarization that is held responsible for the lift of the Mg^{2+} block of the NMDA-receptor channel, which subsequently opens and allows a sustained influx of Ca^{2+} (Ref. c).

When ATP-dependent efflux of Ca^{2+} and active uptake of Ca^{2+} by the mitochondria, endoplasmic reticulum or nuclear envelope fails, Ca^{2+} levels will remain elevated, producing a range of consequences. One pathway of cytotoxic Ca^{2+} leads to generation of reactive oxygen species via activation of NOS and the formation of excessive amounts of NO. Elevated Ca^{2+} in mitochondria uncouples oxidative phosphorylation, which leads to further decrease of energy supply and increase of free radicals. These free radicals damage cellular membranes by lipid peroxidation. A second cytotoxic pathway that is activated as a result of Ca^{2+} overload leads to the sustained activation of a large range of Ca^{2+}-dependent enzymes, such as lipases, proteases, endonucleases and other catabolic enzymes that collectively have detrimental consequences for cell function, membrane structure and the cytoskeleton, and ultimately lead to necrosis.

Cell death in the ischaemic penumbra is, in part, also the result of apoptotic processes. DNA damage via endonucleases or free radicals triggers a complex self-destructive process involving gene expression[d]. As a consequence neurones die apoptotically. There is growing evidence that mitochondria are key structures for induction of this programmed cell death[e]. Moderate reductions of mitochondrial ATP production can trigger apoptotic mechanisms[f]. Recent studies point to the release of caspases, cytochrome c and apoptosis-inducing factor from mitochondria as initiators of apoptotic cell death[g].

When blood flow is restored, oxygen can enhance the biochemical reactions that generate free radicals. Another component that contributes to cell damage is inflammation. In the ischaemic zone, endothelial adhesion receptors are upregulated and white cells adhere to the wall of blood vessels, invade the parenchyma and release cytotoxic cytokines, such as tumour necrosis factor α, interleukin (IL) 1, and IL6 (Ref. h). In conclusion, ischaemic brain damage is multidimensional in origin and offers a broad range of targets for neuroprotective intervention.

(Online Fig. I.)

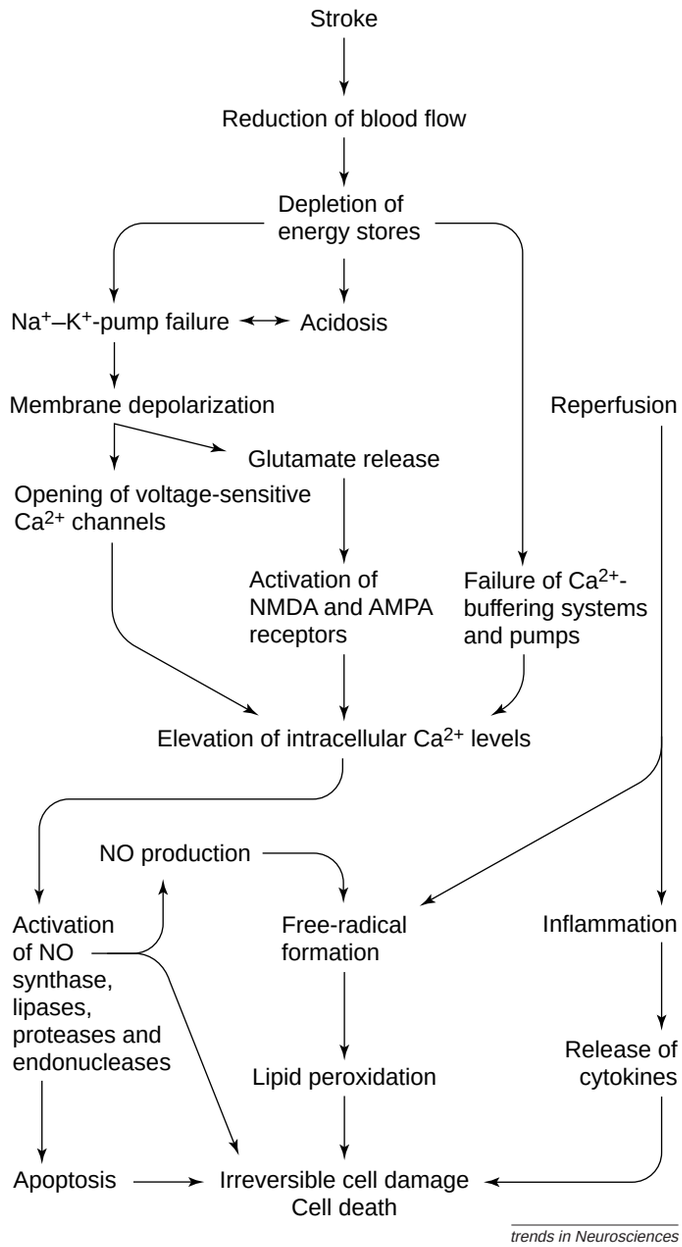

Fig. I. ***Neurotoxic cascade in the ischaemic penumbra.*** *A complex neurotoxic cascade is triggered by a focal deficit in brain perfusion. Key events are uncontrolled neuronal depolarizations, an overexcitation of glutamate receptors, a build up of intracellular Ca^{2+} levels, the generation of free radicals, the stimulation of several catabolic enzyme systems and the induction of inflammation.*

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NMDA-receptor antagonist that acts as an open-channel blocker, have been studied in Phase III trials. However, the trials were terminated prematurely because of an unfavourable risk–benefit ratio[11].

Eliprodil is a drug that is believed to reduce the action of glutamate by binding to the polyamine site of the NMDA receptor[1]. Results were promising in Phase II trials, but a Phase III trial was halted because sequential efficacy analysis did not demonstrate a significant difference from placebo[30].

Clomethiazole is an anti-epileptic drug that causes neuronal hyperpolarization by enhancing the activity of GABA at $GABA_A$-receptors. The rationale behind its use is that it could inhibit ischaemia-induced neuronal depolarizations and counteract the actions of glutamate. The drug protected against ischaemic cell damage

TABLE 1. Major completed Phase III trials with neuroprotective drugs in acute ischaemic stroke

Drug	Class	Trial	Time window	Duration of treatment	Result	Ref.
Fosphenytoin	Na^+-channel antagonist		4 h	3 days	No improvement of functional outcome at 3 months	2
Nimodipine[a]	Ca^{2+}-channel antagonist	TRUST	48 h	21 days	No improvement of neurological outcome at 6 months	3
		American Nimodipine Study Group	48 h	21 days	No difference in mortality or neurological outcome at 21 days	4
		German–Australian Stroke Trial	48 h	21 days	No improvement of neurological outcome at 21 days	5
		Nimodipine in Acute Ischemic Hemispheric Stroke	48 h	21 days	No improvement of neurological and functional outcome at 12 months	6
		NEST	48 h	21 days	No improvement of neurological and functional outcome at 3 months	7
		INWEST	24 h	21 days	Unfavourable outcome in the nimodipine groups	8
		VENUS	6 h	10 days	No improvement of functional outcome at 3 months	9
Flunarizine	Ca^{2+}-channel antagonist	FIST	24 h	4 weeks	No improvement of neurological and functional outcome at 6 months	10
Selfotel (CGS 19755)	Competitive NMDA-receptor antagonist	ASSIST	6 h	bolus	Unfavourable risk–benefit ratio	11
Cerestat (CNS 1102)	Non-competitive NMDA-receptor antagonist		6 h	4 h	Unfavourable risk–benefit ratio	Unpublished
Eliprodil	Polyamine-site antagonist at the NMDA receptor		8 h	14 days	No improvement of functional outcome at 3 months	Unpublished
Clomethiazole	Enhances the effect of GABA at the $GABA_A$-receptor	CLASS	12 h	24 h	No improvement of functional outcome at 3 months	12
Lubeluzole	NO-pathway modulator	LUB-INT-9	6 h	5 days	No reduction in mortality at 3 months	13
		LUB-INT-5	6 h	5 days	No reduction in mortality at 3 months	14
		LUB-INT-13	6–8 h	5 days	No improvement of functional outcome at 3 months	15
Tirilazad	Free-radical scavenger	RANTASS	6 h	3 days	No improvement of functional outcome at 3 months	16
		TESS	6 h	3 days	No improvement of functional outcome at 3 months	17
Ebselen	Free-radical scavenger	Ebselen in Acute Stroke	48 h	2 weeks	No improvement of functional outcome at 3 months	18
Ganglioside GM1	Natural constituent of the cell membrane	EST	5 h	21 days	No improvement of neurological and functional outcome at 4 months	19
		SASS	48 h	28 days	No improvement of survival, neurological and functional outcome at 3 months	20
Citicholine	Natural constituent of the cell membrane	Citicholine in Acute Ischemic Stroke	24 h	6 weeks	No improvement of functional outcome at 3 months	21
Piracetam	Acts at the cell membrane and elevates cAMP levels	PASS	12 h	12 weeks	No improvement of neurological outcome at 4 weeks	22
Enlimomab	Murine antibody to endothelial adhesion molecule 1	EAST	6 h	5 days	Unfavourable risk–benefit ratio	23

[a]Only trials enrolling more than 250 patients are listed.

in animal models of permanent and transient focal brain ischaemia[31,32]. A large Phase III trial, involving 1350 patients, produced negative results[12]. A *post hoc* analysis suggested a beneficial effect in patients with severe stroke (total anterior circulation syndrome), which was the reason for initiating a new trial, the North American Clomethiazole Acute Stroke Study-Ischaemia (CLASS-I). This study aims to include 1200 patients with a total anterior circulation syndrome.

NO-pathway inhibitors and free-radical scavengers

The neuroprotective effects of lubeluzole can be explained, at least partially, by a downregulation of the NO synthase (NOS) pathway, which reduces NO-related neurotoxicity[33]. In a small Phase II trial, a dose of 7.5 mg lubeluzole given within 6 h of the first symptoms, followed by 10 mg per day for five days, was associated with reduced mortality. A double-dose regimen, which yielded a plasma concentration equivalent to the levels

associated with neuroprotection in rats, was associated with increased mortality[36]. Although this was probably caused by an imbalance of randomization that was unrelated to the drug, three large Phase III trials of lubeluzole, involving 3177 patients, were conducted with the 7.5 mg dose. All three trials failed to demonstrate a beneficial effect of lubeluzole on the primary outcome parameters[13–15], and further clinical development has been abandoned (T. Wessel, pers. commun.).

Tirilazad is a non-glucocorticoid 21-aminosteroid lipid-peroxidation inhibitor that acts as a free-radical scavenger. In animals treated within 10–15 min of focal ischaemia this drug reduced infarct volume[13]. However, it did not improve overall functional outcome in two large Phase III studies[16,17]. Because it was suggested that the lack of efficacy might be caused by the use of a dose that was too low (6 mg/kg/day for 3 days), higher doses were tested. These trials were stopped prematurely because of safety problems and further clinical study of tirilazad in ischaemic stroke has been suspended[37].

The seleno–organic compound, ebselen, which has antioxidant activity through a glutathione-peroxidase-like action, was studied in Japan. This drug appeared to improve outcome at one month, but not at three months after the start of treatment[18]. Further efficacy studies with this compound might be justified.

Drugs that mainly act at the cell membrane

In preclinical studies, the ganglioside, GM1, conferred protection against ischaemic and excitotoxic insults[38]. However, two major Phase III trials produced negative results[19,20]. Because of concerns regarding a possible association with the development of Guillain–Barré syndrome[30], GM1-ganglioside product licences have been suspended.

After a number of small inconclusive clinical trials with citicholine (cytidine-5-diphosphocholine or CDP-choline), a multicentre dose-finding study in the USA suggested a better functional outcome in stroke patients receiving 500 mg citicholine per day given orally for six weeks[39]. However, this result could not be reproduced in a pivotal trial involving 394 patients[21].

Piracetam is another compound that mainly acts on cell membranes of both neurones and blood cells[40]. A placebo-controlled multi-centre study in Europe failed to show an improved outcome at three months[22]. *Post hoc* analysis suggested an improvement in neurological outcome in a subgroup of patients treated with piracetam within 6 h of the onset of stroke. A new Phase III trial, PASS-2, has recently been initiated in order to confirm these results.

Anti-inflammatory agents

Within hours, endothelial adhesion molecule 1 (ICAM1) levels are increased in the zone of focal cerebral ischaemia, which allows an influx of white cells into the ischaemic brain area. Cytokines released from the invaded white cells contribute to brain-tissue damage. ICAM1 antibodies reduced infarct volume in rats, only when the model included reperfusion, but not with permanent middle-cerebral-artery occlusion[41]. Enlimomab, a murine monoclonal antibody against ICAM1, has been studied in a Phase III trial. Yet again, the results in the clinical situation did not fulfil the expectations generated in the laboratory[23]. There was even a trend for early neurological deterioration in patients receiving active treatment. A probable explanation is that the murine antigens present in the enlimomab preparation themselves provoked an inflammatory response that cancelled out any beneficial effects by raising body temperature.

Why were the trials negative?

Animal models

Because all the Phase III stroke trials with neuroprotective drugs have failed to live up to their promise, one could argue that the animal models that have been used to test these substances have no predictive value. Focal ischaemia models can be broadly categorized into two types: permanent and reversible[42]. In patients, both types of focal brain ischaemia can occur[43,44]. Both forms of insult can produce a potentially salvageable penumbra. In the transient-occlusion model, reperfusion injury also adds to the damage. For most of the drugs mentioned above, neuroprotective activity has been demonstrated in different types of animal models, including permanent and reperfusion models of middle-cerebral-artery occlusion. However, animal models will never mimic the clinical situation and, therefore, these models should be regarded merely as a method to screen whether a particular compound has the ability to rescue neurones in the ischaemic penumbra when administered after the insult. Although these animal models are indispensable when investigating these compounds, experiments designed to measure functional outcome three months after the ischaemic insult in a larger number of animals, as required for Phase III trials in patients, cannot be justified because of ethical, practical and economic reasons. Infarct volume, which is the most commonly used endpoint in the animal models of focal brain ischaemia, might have little relevance to functional outcome in patients.

Heterogeneity of the stroke population

Animal data are usually collected in healthy laboratory rats of the same age, in which a standardized amount of focal cerebral ischaemia is induced by a reproducible intervention. In contrast, aetiology, location and severity of ischaemic stroke in patients is very heterogeneous. Young and elderly patients are grouped together. It is well known that elderly patients tend to have a worse outcome than younger patients because they have comorbidities that heavily affect outcome. Some patients have a large cortical infarction, whereas others have a lacunar infarction with a completely different prognosis[45]. Some patients have a poor collateral circulation and, hence, a smaller penumbra or no penumbra at all[46,47]. Some patients show spontaneous reperfusion in the early stages after stroke and tend to have a better clinical outcome than those without reperfusion[43]. It is also hardly surprising that no benefit can be demonstrated when an operation designed to correct a particular pathophysiological disturbance is performed in a group of patients, many of whom do not have that disturbance. For example, one in four patients enrolled in a trial with clomethiazole had lacunar white-matter infarctions[12], where there are no neuronal $GABA_A$ receptors to be stimulated.

Other factors that could aggravate brain damage

In animal studies, other variables might affect infarct size and outcome, such as blood pressure, body temperature and oxygenation, which are all carefully controlled during the experiments. It is known that a reduction in blood pressure, hyperglycaemia, hypoxia and increased body temperature can all aggravate cerebral

damage[48,49], and might override any beneficial effect of a neuroprotective agent[50]. However, protocol-specified management of these variables has been neglected in all Phase III stroke trials conducted so far.

Therapeutic dose and adverse effects

Doses of neuroprotective drugs that limit infarct size in animals are usually associated with adverse effects that can limit tolerable doses and prohibit their clinical use. Psychomimetic side-effects were the main reason for the premature termination of trials with NMDA-receptor antagonists. Some side-effects clearly override the putative beneficial effect of a neuroprotective drug. Examples are the detrimental haemodynamic consequences of intravenous nimodipine[8] and an inflammatory reaction associated with the administration of enlimomab[23]. Normally, such problems should be detected in properly conducted Phase II trials, but there is often so much pressure from senior management in pharmaceutical companies to rush for registration that well-conducted Phase II trials are often neglected.

In some trials, suboptimal doses are used because too much emphasis is placed on safety aspects, although side-effects might be acceptable or properly controlled in an acute care setting. This could account for the failure of lubeluzole, where a possible misinterpretation of limited Phase II data and concerns about QTc-interval prolongation on the ECG led to the decision to use a dose regimen that was probably below its neuroprotective threshold[13–15,36]. Another problem is that side-effects can limit the duration of treatment with a neuroprotective drug. Although it is not known exactly how long neuroprotective therapies should last, fear of side-effects, such as sedation, can shorten the duration of treatment to levels that are insufficient for protecting the penumbra. For example, clomethiazole was administered for 24 h (Ref. 12), although it had been demonstrated that excitatory-amino-acid levels in the ischaemic area could remain grossly elevated for at least six days after the onset of stroke[51].

Therapeutic time window

In many animal studies some drugs are effective only if given before or very early (between 15 min and 2 h) after the insult. Typical examples are nimodipine, tirilazad and NMDA-receptor antagonists[16,26,52]. Other compounds, such as lubeluzole, are still effective in reducing ischaemic brain damage when given up to 6 h after the onset of ischaemia[34,35].

Although the penumbra in humans can exist for a longer period than in rodents, at least up to 48 h in studies using PET (Ref. 53) and perhaps several days in studies using magnetic-resonance spectroscopy[54], *post hoc* analyses of a number of trials suggest possible benefit in subgroups of patients treated within a shorter therapeutic time window than defined in the protocol[20,22,27]. Because cell loss in the penumbra is a progressive process, it is expected that the sooner a neuroprotective drug is given, the better the results that will be obtained. A therapeutic effect might have been missed in studies that allowed long inclusion times.

Future prospects

In view of the fact that it is not possible to translate from the animal model to the clinical situation, it appears that the overall disappointing results of clinical trials that have accumulated over the past decade are probably due to protocol and dosage problems. More attention should be paid to properly conducted Phase II trials in order to obtain sufficient information regarding therapeutic time window, dosage, duration of therapy and safety. In small sample sizes of patients, this information might be obtained by invoking surrogate parameters. These include imaging techniques that visualize a potentially salvageable penumbra, such as combined diffusion weighted and perfusion MRI (Refs 47, 55–57), and perhaps the determination of serum levels of enzymes that are released during the course of ischaemic brain damage, such as neurone-specific enolase and S100 (Ref. 58). No compromise should be made with respect to reducing the dosage or duration of treatment below the therapeutic threshold in order to avoid side-effects.

Although there is evidence that the penumbra in humans can exist for a longer period than in rodents, the animal experiments indicate that treatment should be started within the first few hours in order to have any chance of success. Neuroprotective drugs should be administered as long as the ischaemic cascade occurs, which can be as long as six days[51,54]. In addition, physicians should realize that the administration of a neuroprotective drug alone is not sufficient to improve patient outcome. It is difficult to accept that in pivotal stroke trials patients are still dying from aspiration pneumonia because some centres do not use a protocol for the prompt detection of swallowing difficulties. Failure to treat elevated body temperature can also counteract the beneficial effects of a neuroprotective drug[50,59]. Thus, optimal standard care is a prerequisite for the success of a stroke trial, and, therefore, pivotal trials with neuroprotective drugs should be performed in stroke (care) units[48,49,60]. In addition, we should abandon the unrealistic idea that a pharmacological intervention in stroke should be applicable to all stroke types. Neuroprotective trials should be conducted in patients who are likely to have the pathophysiological disturbance that the compound was designed to treat. By using combined diffusion-weighted and perfusion MRI we should be able to identify more rationally appropriate candidates for neuroprotective therapies.

Combination therapy

All neuroprotective agents studied so far target a specific pathway of the ischaemic cascade. It is evident that the administration of either an NMDA-receptor antagonist or a voltage-dependent Ca^{2+}-channel blocker will not be able to control excessive neuronal Ca^{2+} accumulation completely. Although these compounds can reduce infarct size in animal models, we should not expect that any single drug that interferes with a specific event in the ischaemic cascade will have a large clinical impact. In fact, the effects might not be measurable with the crude clinical outcome measures that are currently used, such as the Modified Rankin Scale, the Glasgow Outcome Scale or the Barthel Index.

Instead of continuing with single drug trials (Table 2), it might be more rewarding to explore treatments using a combination of reperfusion with neuroprotection and a cocktail of carefully selected neuroprotective drugs. Animal studies have shown that combination therapies have synergistic effects. Examples are the combination of lubeluzole and diaspirin-crosslinked haemoglobin[61]; thrombolysis with recombinant tissue plasminogen activator (r-tPA) and a glutamate-receptor antagonist[62,63]; and the combination of a glutamate-receptor antagonist (MK801) with basic fibroblast growth factor[64],

TABLE 2. Acute stroke Phase III trials with neuroprotective drugs in progress

Agent	Class	Trial	Company
GV150526	Glycine-site (NMDA-receptor) antagonist	GAIN	Glaxo Wellcome
Clomethiazole	Enhances the effect of GABA at the $GABA_A$-receptor	CLASS-I	Astra
Magnesium sulfate	Blocks glutamate activity at the NMDA-receptor	IMAGES	None
Piracetam	Acts at the cell membrane and elevates cAMP levels	PASS-2	UCB
BMS-204352	K^+-channel-opening compound	POST-010 and POST-011	Bristol Myers–Squibb
Citicholine	Natural constituent of the cell membrane	Phase III trial of citicholine 2000 mg versus placebo	Interneuron Pharmaceuticals
Trofermin	Binds to basic fibroblast-growth-factor receptors	Phase II/Phase III trial	Wyeth–Ayerst

nimodipine[65], GABA-receptor agonists[66], tirilazad mesylate[67] or citicholine[68]. However, this approach would mean that pharmaceutical companies would have to work together instead of competing with each other and that the authorities have to agree to conduct trials with compounds that have not shown efficacy on their own, with the exception of the thrombolytic drug, r-tPA, which is beneficial in a small number of ischaemic stroke patients[69,70].

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LETTERS TO THE EDITOR

Cholinergic correlates of consciousness: from mind to molecules

In their recent article, Elaine Perry and her co-authors[1] illustrate elegantly that ACh is one of the important neurotransmitters that regulate consciousness. One line of reasoning given is that many anesthetics appear to operate through an ACh-mediated mechanism. These authors provide us with a concise and useful summary of ACh-mediated mechanisms of anesthesia. However, no certain conclusion can be drawn about the underlying mechanism of consciousness on the basis of the literature that deals only with ACh. So does a possible answer lie outside the literature on ACh?

Stuart Hameroff[2] has proposed a mechanism for anesthesia that is independent of a particular neurotransmitter. His proposal is that anesthetic gas molecules inhibit quantum states produced by endogenous Van der Waals dispersion forces, which occur